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WINTER RADIATION EXTINCTION AND REFLECTION IN A BOREAL PINE CANOPY: MEASUREMENTS AND MODELLING

J. W. POMEROY AND K. DION*

National Hydrology Research Institute, Environment Canada, 11 Innovation Blvd., Saskatoon, Saskatchewan, S7N 3H5, Canada

ABSTRACT

Predicting the rate of snowmelt and intercepted snow sublimation in boreal forests requires an understanding of the effects of snow-covered conifers on the exchange of radiant energy. This study examined the amount of intercepted snow on a jack pine canopy in the boreal forest of central Saskatchewan and the shortwave and net radiation exchange with this canopy, to determine the effect of intercepted snow and canopy structure on shortwave radiation reflection and extinction and net radiation attenuation in a boreal forest. The study focused on clear sky conditions, which are common during winter in the continental boreal forest. Intercepted snow was found to have no influence on the clear-sky albedo of the canopy, the extinction of short wave radiation by the canopy or ratio of net radiation at the canopy top to that at the surface snow cover. Because of the low albedo of the snow-covered canopy, net radiation at the canopy top remains positive and a large potential source of energy for sublimation. The canopy albedo declines somewhat as the extinction efficiency of the underlying canopy increases. The extinction efficiency of short wave radiation in the canopy depends on solar angle because of the approximately horizontal orientation of pine branches. For low solar angles above the horizon, the extinction efficiency is quite low and short wave transmissivity through the canopy is relatively high. As the solar angle increases, extinction increases up to angles of about 50°, and then declines. Extinction of short wave radiation in the canopy strongly influences the attenuation of net radiation by the canopy. Short wave radiation that is extinguished by branches is radiated as long wave, partly downwards to the snow cover. The ratio of net radiation at the canopy top to that at the snow cover surface increases with the extinction of short wave radiation and is negative for low extinction efficiencies. For the pine canopy examined, the daily mean net radiation at the snow cover surface became positive when daily mean solar angles exceeded 22° in late March. Hence, canopy structure and solar angle control the net radiation at the snow cover surface during clear sky conditions and will govern the timing and rate of snowmelt. Models of intercepted snow sublimation and forest snowmelt could beneficially incorporate the canopy radiation balance, which can be extrapolated to stands of various canopy densities, coverage and heights in a physically based manner. Such models could hence avoid 'empirical' temperature index measures that cannot be extrapolated with confidence.

KEY WORDS solar radiation extinction; solar radiation reflection; boreal forest; net radiation modelling; albedo; snow interception; snowmelt

INTRODUCTION

Broadly defined, the boreal forest is the largest terrestrial biome on earth, covering about 15% of the land area. The biome is dominated by winter and snow covered for more than five months each year. The high latitude of most boreal forests results in low solar angles above the horizon and long nights for much of this snow-covered period. The large extent, low mid-winter radiation inputs and seasonally frozen hydrology make the energetics of snow in the boreal forest important to hydrological and climatological models that are concerned with continental-scale water fluxes. Large areas of the boreal forest are dominated by

* Present address: Dept of Geography, McGill University, Montreal, Quebec, Canada.

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coniferous tree species with evergreen characteristics; the pine, spruce and fir tree. The retention of needles throughout the winter provides stands of these trees with the ability to intercept and retain falling snow and to severely limit the short wave radiation reaching the surface snow beneath the canopy (Kuz'min, 1963; Meiman, 1970).

Snowmelt and sublimation of intercepted snow are two processes of great importance to the accumulation and ablation of boreal snow covers and to the resulting water fluxes in the forest after melt. Predicting the energetics that govern fluxes of snowmelt and sublimation of intercepted snow requires an understanding of the effect of conifers (pine, spruce, fir) on the exchange of radiant energy. In eastern Canadian forests the energetics of melt under a deciduous forest canopy (Price, 1988) and an open, subarctic forest canopy (Petzold and Wilson, 1974) have been measured and discussed. These approaches indicated that calculations of radiant energy fluxes for canopy and surface require knowledge of the reflection of short wave radiation from both canopy and underlying surface snow, and the transmission and or absorption of radiant energy through the canopy. Petzold and Wilson (1974) suggested that canopy temperature alone was sufficient to calculate net radiation at the snow surface, whilst Price (1988) showed that incoming solar radiation was needed in addition.

Hashimoto *et al.* (1994) measured and modelled downward long wave radiation in deciduous and coniferous forests during snowmelt, finding that melt rates were increased under the coniferous forests because of higher downward long wave radiation fluxes under the conifers. The effect of canopy coverage on the downward emission of long wave radiation was emphasized in their model. Hardy *et al.* (in press) weighted the fractional contribution of long wave radiation above the canopy to that below the canopy using canopy coverage to drive a physically based boreal forest snowmelt model. They found that estimated sensible and latent heat fluxes to the subcanopy snow surface were generally opposite in sign and similar in magnitude and that radiation dominated the energetics of melt.

Fresh snow in open fields is typically considered to have an albedo from 0·6 to 0·9 (Winther, 1993). Snow intercepted on forest canopies differs however; Leonard and Eschner (1968) reported that the albedo of a freshly snow-covered pine stand in New York State remained below 0·2. Harding and Pomeroy (1996) confirmed low winter albedos for coniferous canopies in the boreal forest, suggesting multiple scattering of light within the canopy as a possible reason for the low albedo. The characteristics of light scattering that result in this low albedo have not been fully examined despite important implications for climatology and hydrology. Using GCM simulations, Bonan *et al.* (1992) and Thomas and Rowntree (1992) predicted that removal of the boreal forest canopy would strongly increase spring albedo and hence decrease spring air temperatures on a global basis. Harding and Pomeroy (1996) showed the strongly positive net radiation over a pine canopy contrasted with the strongly negative net radiation over a frozen, snow-covered lake in the boreal winter. The strong correlation between net radiation beneath the canopy and air temperature measured near the canopy has been presumed to be the physical basis for the success of empirical temperature index models in calculating snowmelt rates in heavily forested catchments (Male and Gray, 1981; Price, 1988) and the source of energy for sublimation of intercepted snow (Leonard and Eschner, 1968; Lundberg and Halldin, 1994; Pomeroy and Gray, 1995). Price (1988) suggested that melt under deciduous canopies in eastern Canada was dominated by net radiation and that sensible and latent heat fluxes could be neglected.

Some measurements that describe the radiant energy fluxes under boreal coniferous canopies have been descriptive (Constabel and Lieffers, 1996) and have not tried to relate canopy structure to the extinction of short wave radiation or attenuation of net radiation in a physically based manner. Other studies have modelled solar radiation through boreal conifer canopies in an intensive physical manner, using a combination of geometrical optics and radiative transfer models to account for extinction by canopy elements and the influence of canopy gaps on transmittance through the canopy, the most recent and local example being that of Ni *et al.* (in press). While the model developed by Ni and co-workers demonstrates well the effect of canopy architecture on short wave radiation transmission and the heterogeneity of extinction, it does not address the influence of intercepted snow in the canopy, nor is it readily applicable using normal forest inventory measures.

It is the purpose of this paper to describe:

(i) the transmission and reflection of short wave radiation through a boreal pine canopy in winter;

(ii) the influence of intercepted snow and solar angle on this exchange; and

(iii) the effect of short wave exchange and extinction on the net radiation at the snow surface beneath the canopy.

Recent measurements of net and short wave radiation and intercepted snow load in the boreal forest of central Saskatchewan will be used to illustrate the fluxes and develop simple models of radiation exchange that may be applied in distributed hydrological models and land surface parameterizations of climatological models.

THEORY

The albedo is the dimensionless reflectance of a surface, defined as the ratio of reflected short wave radiation flux, $S\uparrow$ (W m^{-2}) to that incoming to the surface, $S\downarrow$ (W m^{-2}), where the albedo α is found as

$$\alpha = \frac{S\uparrow}{S\downarrow} \tag{1}$$

The difference $S\downarrow - S\uparrow$ is generally considered to be the short wave energy absorbed by the surface. However, for a winter boreal forest, the 'absorbed' short wave radiation includes short wave radiation transmitted downwards through the canopy and not reflected by the snow cover, and that reflected by the snow cover and not transmitted back up through the canopy.

Several researchers have considered the transfer of radiative energy through canopies, most recently for conifers, in order to calculate the area of needles from the transmittance, or to determine the photosynthetic radiation available at the canopy bottom (Black *et al.*, 1991; Chen and Black, 1991; Nel and Wessman, 1993; Smith, 1993; Smith *et al.*, 1993; Ni *et al.*, in press). Others have described the effect of snow suspended in the lower atmosphere on radiative exchange (Pomeroy and Male, 1988). The Bouger–Lambert Law describes the transmission of light through a scattering medium and may be applied in this case since the scattering elements (needles, branches, clumps of intercepted snow) are small in comparison to the light path through the canopy. Many forest researchers have used the Bouger–Lambert Law in various forms, the form of expression depending on whether the research emphasis was radiation transmission through canopies or the detection of canopy structure. Here the law is expressed in terms of extinction coefficients and extinction efficiencies of canopies as related to transmissivity for clear sky conditions. The *transmissivity* is the dimensionless ratio of radiation transmitted through the canopy to that incident upon it, the *extinction efficiency* is the ratio of radiant flux scattered to that which actually intercepts the surface of the canopy and the *extinction coefficient* is the horizontal surface area of canopy per unit volume multiplied by the extinction efficiency (van de Hulst, 1957).

The transmissivity, τ may be found as,

$$\tau = \frac{S\downarrow_s}{S\downarrow - S\uparrow} = e^{(-\mu l)} \tag{2}$$

where $S\downarrow_s$ is the short wave radiation incident upon the snow cover beneath the canopy, μ is the extinction coefficient (m^{-1}) and l is the path length of radiation transmission. This equation presumes that all short wave radiation passes through a scattering medium (forest canopy) rather than through gaps in the canopy. Since most boreal coniferous forests have canopy gaps, Equation (2) is approximate and the extinction coefficient should be considered an effective value for the whole canopy including gaps. For direct sun above a forest canopy, the path length, l, can be found as a function of solar angle above the horizon, θ, and H, the vertical depth of the scattering elements (branches, needles, intercepted snow) where,

$$l = \frac{H}{\sin\theta} \tag{3}$$

The extinction coefficient, μ, is a function of the dimensionless extinction efficiency, Q_{ext}, and the cross-sectional area of scattering elements per unit volume. For the case of canopy + snow as the scattering elements, this relationship has the form,

$$\mu = Q_{ext}\frac{LAI\Omega + L'}{H} = Q_{ext}\frac{LAI'}{H} \tag{4}$$

where LAI is the leaf area index in winter (horizontal area of needles and stems per unit area of ground) and Ω is a leaf and stem clumping factor to account for leaves and stems located directly over each other and hence optically behaving as one object (Nel and Wessman, 1993). L' is the horizontal area of intercepted snow load per unit area of ground and LAI' is the 'effective winter leaf area' index. LAI' corresponds to that cumulative plan area of needles, stems and snow having an effect on radiative transfer. LAI' is equal to $(LAI \times \Omega + L')$. The loading of snow in boreal forest canopies has been discussed by Pomeroy and Schmidt (1993), Lundberg and Halldin (1994), Pomeroy and Gray (1995) and Hedstrom and Pomeroy (in press). These expressions permit the derivation of transmissivity from the solar angle, effective winter leaf area index and extinction efficiency. Solar angle can be calculated using standard techniques and $LAI\Omega$ can be measured for a stand using optical instruments (Smith *et al.*, 1993). However, the effect of intercepted snow load on the winter leaf area index and on the extinction efficiency and the effect of solar angle on the extinction efficiency must be understood to model short wave radiation transmission and scattering in a boreal forest canopy.

Net radiation, Q^*(W m^{-2}), is the balance between short- and long-wave incoming and outgoing radiation at a surface, which can be expressed as

$$Q^* = S\downarrow(1-\alpha) + L\downarrow - \sigma T^4 \tag{5}$$

where $L\downarrow$ is incoming long wave radiation, σ is the Stefan–Boltzmann constant and T is the surface temperature (K). Knowing the net radiation at the snow surface below a canopy, Q_s^*, is necessary for calculations of snowmelt rate and surface snow cover evaporation. Presuming little change in the relatively high surface snow cover albedo during the premelt and early melt condition, then the onset of larger Q_s^* values will be driven by greater long wave radiation emission from the lower canopy. A useful way to describe the net radiation at the canopy bottom (where it is normally unknown) from that at the canopy top (where techniques such as the Brunt Equation are often available to estimate it) is the net radiation ratio, N_r, where

$$N_r = \frac{Q_s^*}{Q^*} \tag{6}$$

The influence of albedo and canopy extinction on N_r is shown in the following expression, where

$$N_r = \frac{S\downarrow(1-\alpha)e^{(-\mu l)}(1-\alpha_s) + C_c\sigma T^4 + L\downarrow(1-C_c) - \sigma T_s^4}{S\downarrow(1-\alpha) + L\downarrow - \sigma T^4} \tag{7}$$

and C_c is the canopy coverage of the sky, and subscript 's' refers to the surface snow cover. It is assumed in Equation (7) that both upward and downward long wave radiation are emitted from canopy surface elements of similar temperatures that may be approximated by T. As Q^* is usually slightly positive during the winter day over the boreal forest (owing to low albedo), N_r must be positive to provide the energy necessary to drive snowmelt under evergreen canopies. Presuming that much of the short wave radiation extinguished within the canopy heats the canopy, increasing T, then extinction of this radiation will increase downward long wave emissions and partially contribute to Q_s^*. Because much of the downwelling short wave radiation that is *not* extinguished by the canopy is reflected by the high albedo snow cover, the implication of Equation (7) is that N_r will increase with the extinction coefficient of the canopy unless the

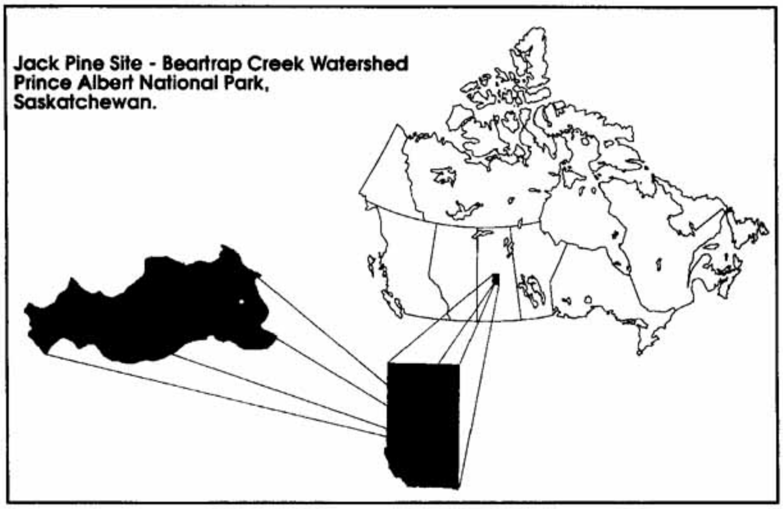

Figure 1. Study site and catchment in Prince Albert National Park, Saskatchewan, Canada

Figure 2. Winter scene in the jack pine canopy showing canopy density

canopy is very sparse and large fluxes of short wave are available to intercept the surface directly. It is expected that the actual relationship between N_r and the extinction coefficient will depend upon canopy density, coverage and height and must be understood to model subcanopy radiation.

METHODS

Site

A mature jack pine (*Pinus banksia*) stand in the mixed-wood southern boreal forest of western Canada was chosen for study. The stand is located at 53·87°N, 106·13°W, within the Beartrap Creek catchment of Prince Albert National Park, Saskatchewan, Canada (Figure 1). The site has an effective winter leaf area index ($LAI\Omega = LAI'$) of 2·2 m^2/m^2, canopy coverage of 82% and an average tree height of 19 ± 3 m (Figure 2). Terrain is level and covered with a sparse undergrowth of deciduous bushes ranging in height from 1 to 2 m. Over the period of study, from November 1993 to March 1994, the low-lying carpet of sphagnum moss and kinnikinnick (bearberry) was covered by a blanket of snow.

Measurements

A 27-m tall tower was erected in the centre of the pine stand as a host for a variety of meteorological measurements (Figure 3). At the top of the tower, two Kipp and Zonen short wave radiometers and one 'Middleton' net radiometer measured the incoming, $S\downarrow$, and reflected, $S\uparrow$, short wave radiation and net radiation, Q^*, respectively. Near the base of the tower, two 'Delta-T' 1-m tube short wave radiometers and one Delta-T 1-m tube net radiometer were mounted 1 m above the ground to measure the subcanopy incoming, $S\downarrow_s$, and reflected, $S\uparrow_s$, short wave radiation and the subcanopy net radiation, Q_s^*, respectively. Use of tube radiometers below the canopy provides a more representative measurement of radiation than standard dome radiometers and averages out small-scale variability in radiant intensity. The radiometers were cleaned during weekly visits to the site and often more frequently when snowfall occurred. Careful notes were taken to specify periods when the radiometers were clear of snow. On certain

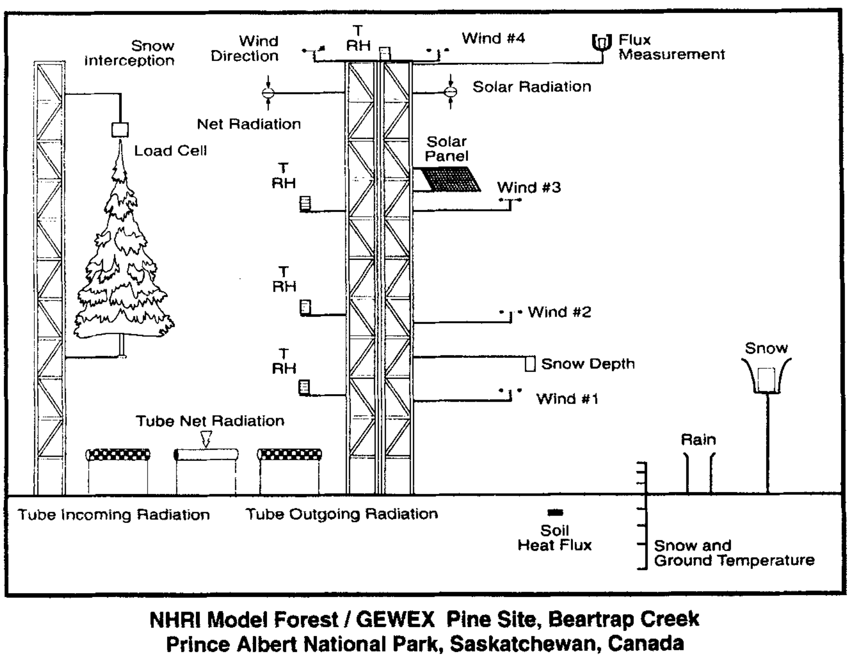

Figure 3. Instrumentation in the canopy and the weighed tree apparatus

occasions, frost covered the upward facing radiometers in the morning and may have raised estimates of albedo and transmittance somewhat.

To estimate the mass of intercepted snow in the canopy, two techniques were used. For the first, two Logitech 'Fotoman' digital cameras were installed on the tower at 12 and 18 m height to provide oblique photographs of the canopy. These cameras were triggered by 5-V pulses from 'Campbell' microloggers to provide an image at noon each day of the canopy. A Fotoman camera can store 32 images and must be downloaded to a computer. The digital images provide the snow-covered area of the canopy, which can be related to the mass of intercepted snow (Pomeroy and Schmidt, 1993). The second technique used the mass of a cut 11-m tall jack pine tree. The tree was suspended from a second 15 m tall tower by a cable, connected in-line to a load cell (Figure 3). The load cell measured the mass of the freely hanging tree and any snow accumulation on the tree. The tree was felled when the daily average air temperatures were well below freezing and an insoluble resin was applied to the severed base of the tree to prevent mass and moisture loss (Pomeroy and Schmidt, 1993; Pomeroy *et al.*, 1994).

Several other sensors were placed above, below and within the canopy to measure vertical and horizontal wind speeds, air temperature, relative humidity, soil and snow temperatures and the snow particle flux (Pomeroy *et al.*, 1994). Most instruments were controlled by Campbell Scientific 21X microloggers. Data were retrieved from the instruments once per minute and averaged by the micrologger to provide half-hour averages. The load cell, connected to a Campbell Scientific CR-10 micrologger, measured the tree's mass every 10 seconds to provide 15 minute standard deviation and averages of the maximum, minimum and mean weight of the tree. This statistical information on tree weight was used to identify periods when high winds, small animals or branch loss disturbed the tree and periods when snow accumulated rapidly or ablated.

Weekly measurements of snowfall and subcanopy snowfall were obtained from Atmospheric Environment Service (AES) nipher-shielded snow gauges, placed beneath the jack pine canopy and in a nearby opening. Ten-point snow surveys under the canopy and in the small clearing supplemented the snowfall measurements with spatially averaged snow accumulation estimates. The difference between snowfall measurements under the canopy and in the clearing was related to the weight of snow on the suspended tree just after snowfall events. Subcanopy snowfall from the AES gauge was compared with snow accumulation surveyed during cold periods and found to be a good areal indicator of subcanopy snowfall. The ratio of difference to weight was therefore used to estimate the canopy snow interception load in mm snow water equivalent on a half-hourly basis.

Figure 4 depicts the weekly average meteorological conditions throughout the winter of 1993–1994 at the

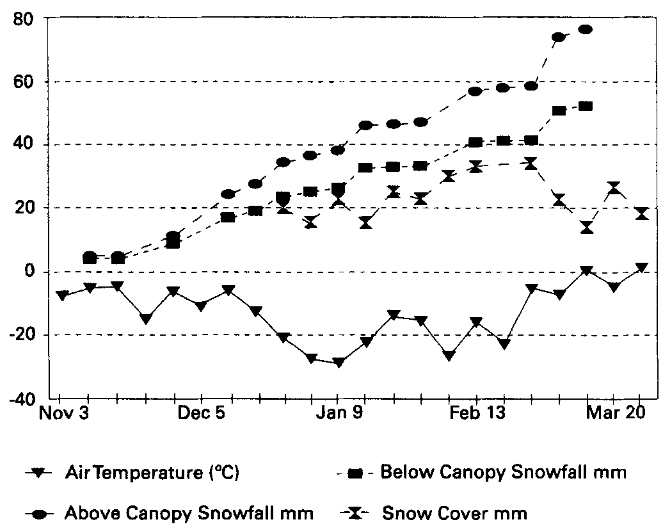

Figure 4. Weekly mean meteorological conditions in the winter 1993–1994 at the jack pine site. Air temperature is measured above the canopy, snow cover is derived from surveys along a line through the jack pine stand

jack pine site. Air temperatures (measured above the canopy) remained below 0°C from November onwards, became extremely cold early in 1994 (−30°C) and finally warmed to 0°C about the last week in March. Weekly snowfall amounts were small, generally less than 10 mm snow water equivalent (SWE), except for a single heavier snowfall during the March melt period. Subcanopy snowfall was substantially reduced by interception, being about 68% of above-canopy snowfall over the winter. As this intercepted snow was not unloaded to the surface upon warming in late winter it is considered to have sublimated via mechanisms described by Pomeroy and Schmidt (1993) and Pomeroy and Gray (1995). Premelt snow cover as derived from snow surveys was slightly less than the subcanopy snowfall, at about 60% of cumulative above-canopy snowfall before melt began. The difference between subcanopy snowfall and snow accumulation is considered largely to be a result of small variations in canopy density between point snowfall measurements and areal-averaged snow surveys, complemented by small surface evaporative losses. The winter sequence of consistently cold days, small snowfall amounts and large interception loss is accompanied by frequent clear skies and is characteristic of the continental boreal forest of western North America.

Determining the effective leaf area index and solar angle of incidence

The $LAI\Omega$ was measured beside the ground solarimeters and radiometer using a 'Licor' LAI-2000 *Plant Canopy Analyser* (Licor, 1992) when the canopy was snow-free. Leaf area index was considered a useful measure of canopy structure because of its potential retrieval from satellite measurements (Running *et al.*, 1986) and physical meaning as a measure of scattering elements. LAI' could not be measured while intercepted snowfall remained in the canopy since the LAI-2000 can not differentiate between the intercepted snow and the sky. The LAI-2000 was calibrated to sky brightness at the top of the tower on a day with uniform low-lying cloud cover while using a 90° view-limiting cap (view was 270°) to shield measurements from the operator and the sun. Measurements were taken at ground level with the same view cap and orientation, within 2 minutes of the calibration readings. Since the LAI-2000 already measures LAI' ($LAI\Omega$), the stand and branch clumping characteristics do not require further calculation (Smith *et al.*, 1993).

Walraven's (1978) FORTRAN program was used to calculate the position of the sun given latitude, longitude, time zone, time of day and time of year, providing mean solar incident angle to correspond to the half-hourly radiation measurements. The program, initially designed to calculate the azimuth and elevation of the sun on the hour, was modified to calculate the location of the sun every minute and to provide half-hour mean values for the solar elevation and azimuth. The calculated elevation was used as the angle of solar incidence throughout the study.

DATA ANALYSIS

Diurnal time-series plots of incoming solar radiation above the canopy and field notes were used to determine periods when the radiometers were snow free and mainly cloud free conditions prevailed. From these periods, a classification scheme describing the relative amount of canopy-intercepted snow was devised from the weighed-tree intercepted snow mass and daily digital images of the canopy. From November to December, these techniques were not available to determine the amount of intercepted snow. Instead, observations in our field notes and measurements of snowfall accumulation, wind speed and air temperature were used to estimate the amount of intercepted snowfall until 24 January 1994.

The mass of intercepted snowfall ranged from 0 g to over 12 kg between November and March (Pomeroy *et al.*, 1994). Owing to periodic power shortages in January and overcast conditions, the study period was limited to days where the intercepted snow mass ranged between 0 and 5 kg. Intercepted canopy load (mm SWE) was calculated from the mass of snow on a single tree (kg) using ratios developed when snowfall occurred just before a snow survey. The *residual* snow is that water equivalent measurement at the ground and unaccounted for owing to interception of sublimation of intercepted snow from the canopy. Residual snow, R (mm SWE) is found as the difference in subcanopy snowfall, P_s (mm SWE) and snowfall above the canopy, P (mm SWE), where,

$$R = P - P_s \tag{8}$$

The canopy intercepted snow load, I (mm SWE) is equal to the residual snow less sublimation, Q_{subl} (mm SWE), where sublimation is a cumulative vertical flux and is negative in sign. Measurements of R just after snowfall include only a small sublimation component and can provide a ratio between canopy snow load and tree snow load, k, where

$$k = \frac{R + Q_{subl}}{M} = \frac{I}{M} \tag{9}$$

and I can hence be found from the mass of the weighted tree. For the winter 1993–1994, k was found to be 0·25 mm/kg on average.

Albedo was calculated using standard techniques [Equation (1)] for the canopy top and bottom. The extinction coefficient of visible radiation was calculated from measurements of incoming and outgoing radiation at the top of the canopy and incoming radiation at the bottom of the canopy following Equations (2) and (3), measured canopy thickness of 10 m (actual thickness of leafed canopy) and calculated solar angle. Extinction efficiency was determined with greater uncertainty using Equation (4), the calculated extinction coefficient and the presumption that the measured $LAI\Omega$ in snow-free conditions (2.2) approximated the LAI' with intercepted snow. The net radiation ratio was determined using measured net radiation from canopy top and bottom and Equations (5) and (6).

Table I indicates the days used for the analysis along with some mean daily conditions for these days. The criteria used in selecting a sample period for the extinction analysis were cloud-free days, variable amounts of intercepted snow and snow-free radiation instruments. In order to include days with a moderate to heavy intercepted snow load, some days that were sunny with a few intermittent clouds were used (24–26 January, 3 February and 15 February). Comparison of half-hourly values of incident short wave flux during these days with those from cloud-free days indicates that the effect of light, discontinuous, intermittent cloud cover is negligible in this analysis. Whilst attempts were made to keep radiometers frost free, there were periods of early morning when this could not be avoided, adding a source of error to the data. The relatively dry climate precluded the heavy hoar-frost accumulations found in some mountain and coastal regions.

RESULTS

Albedo above and below the canopy

The mean daily albedo of the canopy from Table I, indicates that consideration of intercepted snow load explains little of the change in canopy albedo. Although freshly fallen snow in open fields has an albedo of between 80 and 90%, the mean daily albedo of the freshly snow-covered pine canopy fluctuated between 12 and 17%. A relationship between snowfall and canopy albedo is hard to detect; following the moderate snowfall between 21–23 March, the canopy albedo remained at approximately 12%, whilst the highest albedo (17%) occurred on 5 December, a day with relatively little intercepted snow but a low solar angle.

The surface snow cover albedo under the canopy ranged from 58 to 88% over the winter, consistent with that found over open snow fields (Male and Gray, 1981). The albedo varied with the age of snow and the amount of forest litter visible on top of the snowpack. As snow depth increased in early winter, the snow cover albedo increased from near 60% to over 80%, declining in spring as forest litter accumulated on the snow surface and wetness increased in warmer weather.

Half-hourly albedos provide more detailed information on the relationship between canopy albedo and intercepted snow load. Figure 5a shows albedo expressed as a percentage ($\alpha \times 100\%$) and the corresponding intercepted snow load, L (mm SWE), derived from the mass of snow in the weighed tree and Equation

Table I. Days and conditions used in the analysis, winter 1993–1994. Shown are the mean daily solar angle, mass of intercepted snow on the weighed tree, above- and below-canopy incoming solar radiation and albedo

Day	Maximum Daily Solar Angle of Incidence (°)	Mean Daily Mass of Intercepted Snow (g)	Mean Daily Albedo Above Canopy (%)	Mean Global Solar Radiation Above Canopy (W/m^2)	Mean Daily Albedo Below Canopy (%)	Mean Global Solar Radiation Below Canopy (%)
Nov. 15/93	18	~0–500	N/A	138	62	14
Nov. 16/93	17	~0–500	N/A	113	62	14
Nov. 17/93	17	~0–500	N/A	155	62	11
Nov. 23/93	16	~250–750	16	169	67	10
Nov. 24/93	15	~250–750	15	151	64	11
Nov. 25/93	15	~250–750	17	135	63	10
Nov. 26/93	15	~250–750	16	136	61	9
Dec. 5/93	14	~250–750	17	116	68	9
Dec. 6/93	14	~0–500	15	122	67	9
Dec. 7/93	13	~0–500	15	134	66	9
Jan. 24/94	17	4284	15	160	83	13
Jan. 25/94	17	4171	15	105	88	13
Jan. 26/94	17	3567	16	117	86	14
Feb. 2/94	19	4117	16	224	86	15
Feb. 3/94	20	2151	15	130	84	20
Feb. 5/94	20	950	14	171	83	20
Feb. 6/94	21	668	13	222	80	18
Feb. 7/94	21	795	14	233	76	19
Feb. 8/94	21	483	15	217	75	20
Feb. 9/94	21	194	14	215	77	21
Feb. 10/94	22	208	14	212	81	22
Feb. 15/94	23	614	13	154	80	25
Feb. 16/94	24	117	14	219	73	23
Mar. 1/94	29	0	12	287	80	31
Mar. 2/94	29	0	12	270	68	34
Mar. 3/94	29	0	12	295	65	35
Mar. 4/94	30	0	13	285	63	34
Mar. 7/94	31	0	13	308	58	41
Mar. 8/94	31	0	12	294	58	43
Mar. 21/94	36	2499	12	332	82	49
Mar. 22/94	37	1407	12	375	82	50
Mar. 23/94	37	339	12	373	71	55

(9). Some of the highest half-hourly canopy albedos (31%) occur when the canopy is snow free but low solar angles and possible frost interference in measurements occurs. No relationship whatsoever between albedo and intercepted snow load is evident, suggesting that intercepted snow load has an insignificant effect on the albedo of coniferous stands in the boreal forest. A more distinct relationship is shown between half-hourly albedo and extinction coefficient in Figure 5b, where the albedo declines as the extinction coefficient increases. An envelope curve is indicated for which the maximum albedo declines with increasing extinction coefficient. Appreciable scatter is evident in Figure 5 because half-hourly values are used, including times when radiant energy is quite small and measurement errors relatively larger. To minimize these errors Figure 6 shows the daily albedo and the daily extinction efficiency, both calculated from daily totals of short wave fluxes. Although scatter is appreciable, a roughly linear relationship can be discerned between the daily values. When fitted to the extinction efficiency, the measured LAI' of 2·2 and H of 10 m a modelled linear relationship for α as defined in Equation (1) is

$$\alpha = 0{\cdot}193 - 1{\cdot}04 Q_{\text{ext}} \frac{LAI'}{H} \tag{10}$$

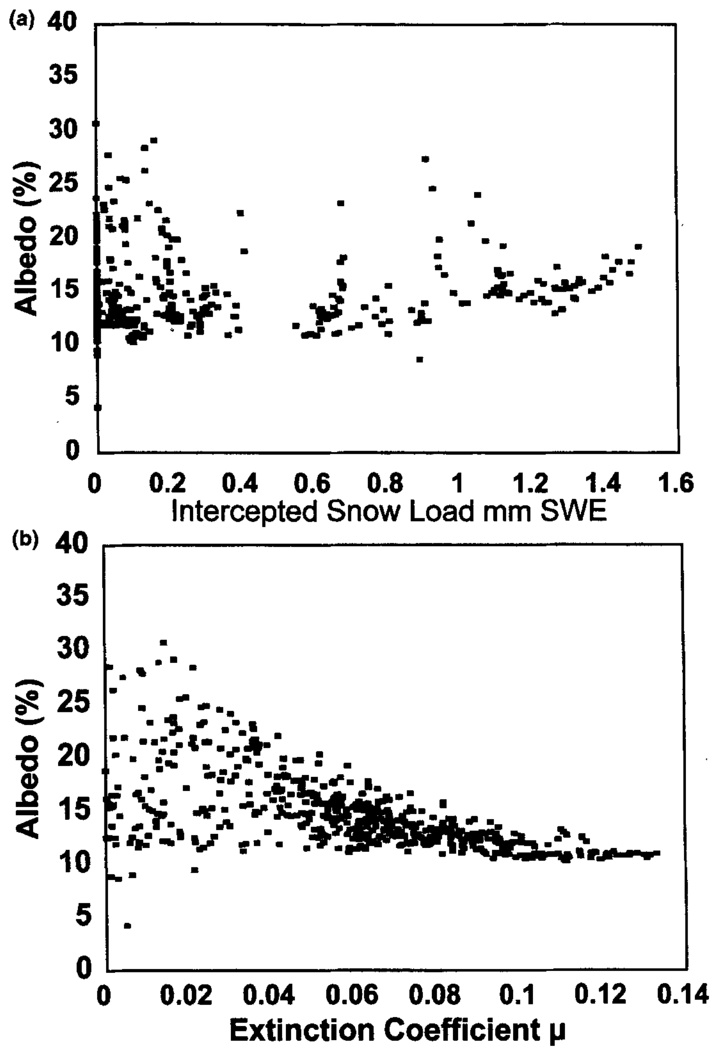

Figure 5. (a) Albedo (expressed as a %) and intercepted snow load (mm SWE), half-hourly values. (b) Albedo and extinction coefficient (m^{-1}), half-hourly values

with an r^2 of 0·69 and a standard error of albedo estimate of 0·009. Although the correlation coefficient is not high, the small standard error suggests that the relationship may be suitable for radiation modelling purposes. An advantage of Equation (10) is that it depends on forest stand parameters, the leaf area and height, which are often part of forest inventory records.

The physical meaning of Equation (10) is that as the extinction efficiency of short wave radiation or the leaf area increases, the albedo declines but a positive relationship between albedo and canopy thickness (where there is no increase in LAI') is indicated. In practice, LAI' and H are somewhat correlated and tend to increase together. The net effect is that as more short wave radiation is extinguished, the albedo becomes smaller. The possibility that greater extinction diminishes emission through the canopy of radiation reflected from the snow surface under the canopy is examined in Figure 7 which compares reflected short wave at the canopy bottom $S\uparrow_s$ and reflected short wave from the canopy $S\uparrow$. For $S\uparrow$ less than 30 W/m^2, the $S\uparrow_s$ from the snow cover is quite small (<2 W/m^2) and insufficient to modify the upward flux measured at the canopy top. For greater reflected values, $S\uparrow_s$ does increase but only up to 5 W/m^2 for a $S\uparrow$ of 45 W/m^2, or roughly 10% of the upward short wave flux from the canopy, if all radiation

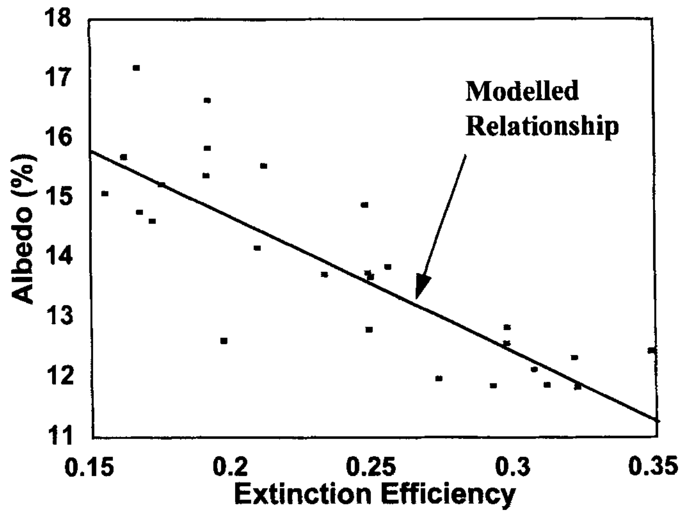

Figure 6. Daily albedo and daily extinction efficiency, both calculated from daily totals of short wave fluxes. Modelled relationship [Equation (8)] shown for comparison

reflected from the snow cover contributed to the upward flux from the canopy. It is clear from Figure 7 that short wave radiation reflected from the snow cover, does not contribute significantly to canopy albedo as the small amounts of radiation reflected from the snow surface would be partly attenuated whilst transmitted through the canopy and reduced from the measurements shown. The variance of albedo with extinction efficiency must therefore be a result of some feature of radiation extinction in the coniferous canopy.

Short wave radiation extinction in the canopy

The dependence of albedo on the canopy extinction coefficient is useful for radiation modelling purposes as this extinction coefficient also controls the penetration of short wave radiation to the underlying snow cover. Black *et al.* (1991) showed that for low solar angles, the extinction coefficient of Douglas Fir stands in coastal British Columbia increased with increasing solar angle. At higher angles this relationship levels

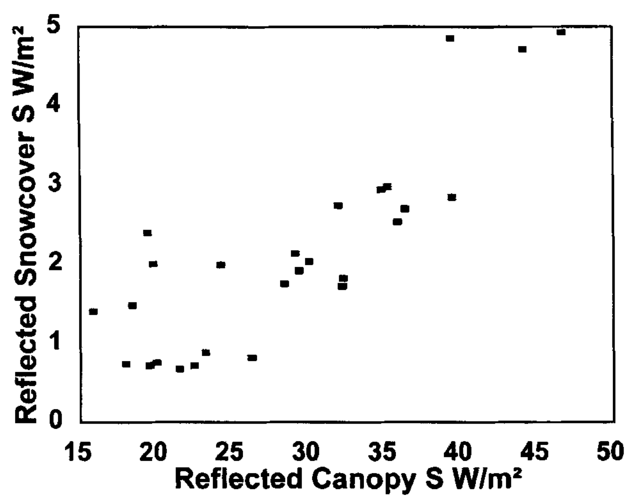

Figure 7. Short wave reflected from the surface snow cover ($S\uparrow_s$) and canopy reflected short wave, ($S\uparrow$)

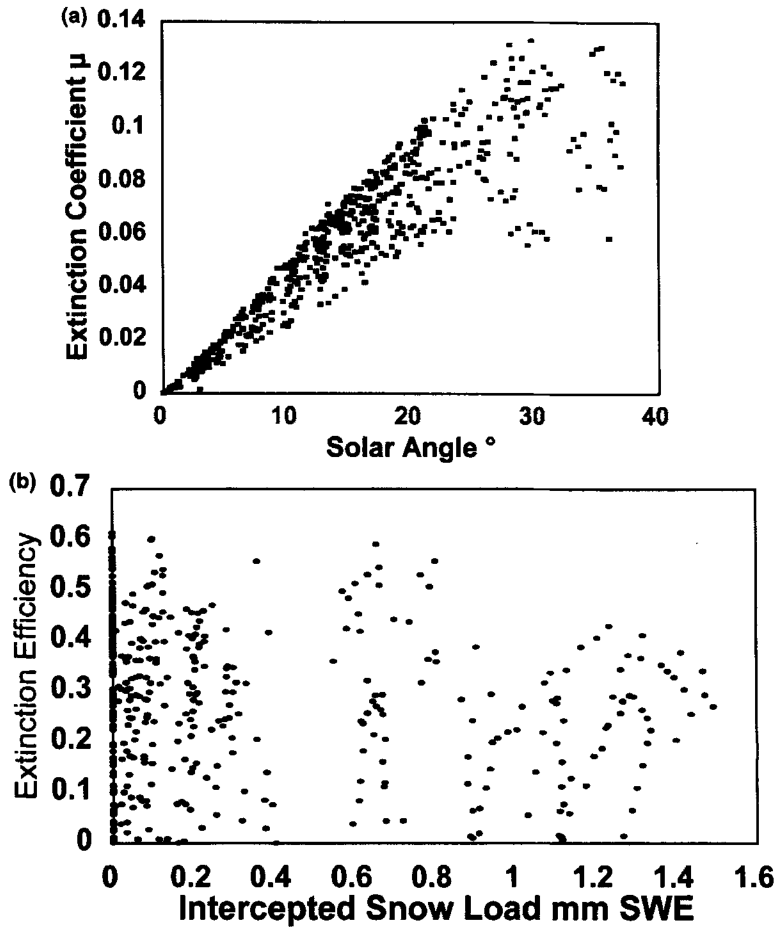

Figure 8. (a) Extinction coefficient (m^{-1}) and solar angle above the horizon (°), half-hourly values. (b) Extinction efficiency and intercepted snow load (mm SWE), half-hourly values

off and reverses. Ni *et al.* (in press) modelled similar conclusions for a boreal jack pine stand. This is expected if needles and branches are oriented primarily in the horizontal plane. In this case their area tangential to the sun and the angular width of solar radiation that intercept the needles/branches controls the 'efficiency' with which radiation is extinguished for a uniform volume of needles/branch. Presuming from geometrical optics that the extinction efficiency of oriented needles will vary with the product of solar angle with respect to the horizontal plane and the intercepted length of the plane, $\theta \cos(\theta)$, the half-hourly extinction coefficient is graphed in comparison to θ in Figure 8a. A roughly proportional relationship is shown for low angles, with increasing scatter and curvature as solar angle increases. The curve indicates that a relationship between extinction and $\theta \cos(\theta)$ is possible but that considerable scatter affects the relationship. To examine possible effects of intercepted snow on the extinction efficiency and hence on the extinction coefficient, Figure 8b shows half-hourly values of extinction efficiency graphed against intercepted snow load. The scatter is considerable and although a small decline in extinction efficiency with snow load can be discerned, in general this effect is negligible and there is no definable relationship between the two variables. Because of the large scatter in the half-hourly values, daily extinction efficiencies were examined along with mean daytime solar angle in order to develop a relationship. Figure 9 shows the mean daily extinction efficiency plotted with the product $\theta \cos(\theta)$. A proportional relationship is indicated, confirmed by a linear regression with an r^2 of 0·88 and standard error of 0·0199 for estimated extinction efficiency, where

$$Q_{ext} = 0{\cdot}781\theta \cos(\theta) + 0{\cdot}0591 \tag{11}$$

and θ is in radians. The relationship is shown by the solid line in Figure 9.

The implications of Equation (11) and an examination of the data are that intercepted snow has little or no effect on extinction of short wave radiation in pine canopies, but solar angle has an extremely important effect on extinction. Because pine needles/branches are oriented, primarily in the horizontal plane, they reflect and scatter light according to the incidence angle of the radiation on the needle. It is seen that at very low solar angles, although the angular area of needle is potentially high, the orientation of the needles/branches is such that very little actual needle area is silhouetted by incoming solar radiation. As solar angle increases, the angular area of needle/branch declines but the orientation of the needles/branches is more normal to the incoming radiation. Equation (11) postulates that a maximum extinction efficiency occurs for solar angles of 49° above the horizon for the jack pine species examined.

Net radiation attenuation in the canopy

The extinction of short wave radiation may be expected to influence strongly the attenuation of net radiation as described in Equation (7). One way to examine this is to calculate the net radiation ratio, N_r, from measured net radiation at the canopy top and above the surface snow cover. To examine whether the load of intercepted snow has any effect on net radiation attenuation in the canopy, half-hourly values of intercepted snow load are plotted against the ratio of net radiation at canopy top to snow cover top in Figure 10. There is possibly a decline in N_r with increasing snow load but the large degree of scatter and low slope of the possible relationship suggest that intercepted snow load is generally inconsequential to the attenuation of net radiation by coniferous forest canopies.

To determine whether the extinction efficiency of short wave radiation has a strong impact on net radiation attenuation, half-hourly values of the two parameters are plotted in Figure 11. The relationship shown is interesting, for low extinction efficiencies (and hence low solar angles and net radiation; Figure 9) there is no apparent trend, but for extinction efficiencies greater than about 0·2, the net radiation ratio increases proportionately to the extinction efficiency. The trend shows decreasing scatter for larger values of extinction efficiency. A linear equation was fitted through the densest part of the trend and is,

$$N_r = 1{\cdot}91 Q_{ext} \frac{LAI'}{H} - 0{\cdot}14 \tag{12}$$

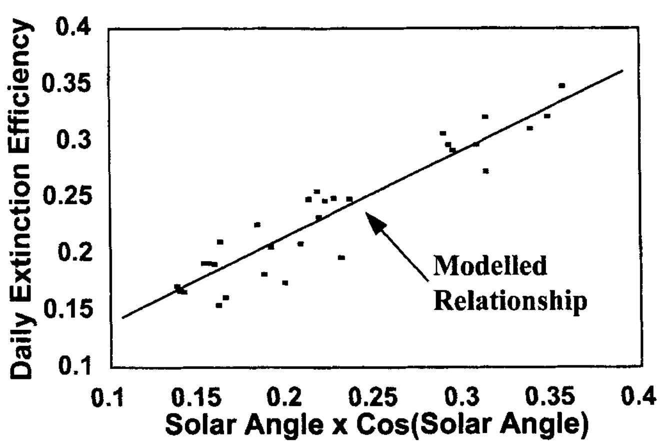

Figure 9. Daily extinction efficiency and mean daily solar angle (radians) times the cosine of solar angle. Modelled relationship [Equation (9)] is shown for comparison

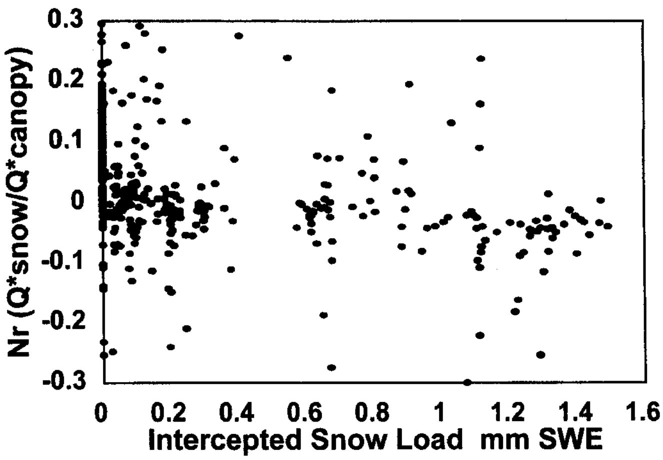

Figure 10. Intercepted snow load (mm SWE) and the ratio of net radiation at canopy top to snow cover surface, half-hourly values

with no statistical fit specified because of the scatter for low N_r. This relationship suggests that N_r may be negative for low extinction efficiencies, near zero for moderate N_r and positive for high N_r. Hence, presuming that snowmelt events occur when above-canopy net radiation is positive, then net radiation above the snow cover only becomes positive when the short wave extinction efficiency is high and therefore when the solar angle is high (but not higher than 50°). Low canopy albedo indicates that extinction of short wave radiation is caused largely by absorption rather than scattering, hence the greater subcanopy net radiation for high short wave extinction conditions is probably owing to downward emission of long wave by the canopy. Pomeroy *et al.* (1994) and Harding and Pomeroy (1996) show, for the same site, that daily positive net long wave radiation beneath the canopy comprises much more than half of the positive net radiation beneath the canopy in the March and April periods. The short wave energy absorbed by the canopy during extinction is partially transformed into download long wave radiation and directed towards the underlying snow cover.

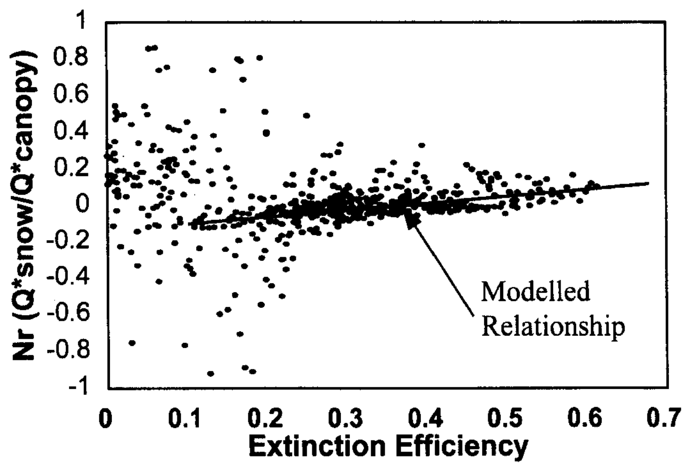

Figure 11. Extinction efficiency of short wave radiation and the ratio of net radiation at canopy top to snow cover surface, half-hourly values. Modelled relationship [Equation (10)] is shown for comparison

DISCUSSION

The implications of the relationships derived here are that for clear-sky conditions in winter and early spring, transmission and reflection of short wave and emission of long wave radiation in boreal coniferous canopies are primarily dependent upon the extinction efficiency of short wave radiation in the canopy. This extinction efficiency in turn is dependent upon the leaf area index, canopy height and solar angle, but not the intercepted snow load. Intercepted snow generally covers existing branch area rather than spreading over the edge to a large degree, hence it cannot greatly increase the effective leaf area. The relatively translucent nature of thin intercepted snow patches compared with pine branches would not add significantly to attenuation of short wave radiation. The horizontal orientation of pine branches leads to relatively low short wave extinction efficiencies at low solar angles; as for other conifers, this extinction efficiency is expected to peak for solar angles of about 50° and then decline with increasing solar angle. The mean daily solar angles at the time of snowmelt (late March in Waskesiu), about 25°, would then be expected to be particularly efficient at extinguishing short wave radiation penetration into the boreal canopy.

The canopy albedo is not dependent upon the load of intercepted snow nor short wave radiation reflected from the surface snowpack. It is presumed that multiple reflections and scattering of light from patches of intercepted snow in the canopy and the high probability of light being reflected from an intercepted snow patch to the underside of an overlying branch cause the load of snow in the canopy to have a negligible effect on canopy albedo despite the high point albedo of snow patches. During clear skies, the canopy albedo declines with increasing extinction efficiency and hence solar angle for winter/spring, increasing the net radiative energy available for sublimation of intercepted snow.

The seasonal change in daylight hours and incoming short wave intensity are expected to be much more important to canopy net radiation than the small change in albedo. During clear-sky conditions the variation in net radiation at the canopy top is governed by variations in incoming short wave radiation, because albedo is low and clear skies imply small incoming long wave radiation and near-black body emission of long wave based on the temperature of the canopy [Equation (7)]. Net radiation for the surface snow cover is relatively unaffected by incoming short wave radiation because of the high albedo, and extinction of incoming short wave radiation by the overlying canopy. However, the relationship between net radiation under the canopy and canopy extinction of short wave radiation suggests that long wave emission from the canopy plays a strong role in governing net radiation at the snow cover surface as suggested by Harding and Pomeroy (1996). Under clear-sky conditions this downward long wave emission from the canopy appears to be strongly related to the extinction of short wave radiation by the canopy. As a result, air temperature is probably not so much a 'driving' factor during snowmelt under coniferous canopies as an indicator of the canopy temperature, and hence long wave emission.

Of the variables considered, solar angle is of overriding importance in governing all of the radiative fluxes in the pine canopy. Because of the strong seasonality to solar angle in the boreal forest of North America, a strong seasonality to radiative fluxes is implied. As hydrological phenomena such as sublimation of intercepted snow and snowmelt are strongly influenced by net radiation, they will be related to the solar angle. Increase in solar angle increases not only the intensity and length of time the canopy is exposed to incoming short wave radiation, but also decreases the albedo, and hence rates of sublimation of intercepted snow are expected to be much higher for high solar angles. Daytime net radiation under the pine canopy does not become positive until solar angles have reached a value of about 22° for the pine forest studied ($LAI = 2{\cdot}2$, canopy thickness = 10 m). As snowmelt is largely governed by net radiation, it is relatively unlikely that snowmelt can begin in the boreal forest until the daily mean solar angle reaches the critical value to permit positive net radiation under the canopy over the daylight hours. Leaf area and canopy height are also important in governing short wave extinction in the canopy and net radiation at the snow cover surface. Canopies with larger leaf areas will extinguish more short wave radiation and consequently have higher net radiation at the snow cover surface. If the leaf area remains constant, taller canopies alone reduce the 'vertical density' of the leaf area and hence reduce extinction and net radiation at the snow cover surface. However, in most cases an increase in the vertical thickness of canopy corresponds with an increase in leaf area index. As a result of canopy structure and the importance of solar angle to radiative fluxes, many snow covers under mature boreal forests are much less sensitive to fluctuations in air temperature than those in adjacent open areas such as clear-cuts and agricultural fields where the sensible heat flux can contribute significantly to melt.

CONCLUSIONS

The following conclusions can be made for the implications of radiation fluxes in conifer canopies in the boreal forest under clear-sky conditions when a snow cover exists under the canopy.

1. Short wave and net radiative exchange in boreal conifer canopies are unaltered by intercepted snow load under clear-sky conditions. It follows that visible and thermal infrared remote sensing will have difficulty detecting the presence of intercepted snow in the boreal forest.

2. Coniferous canopies are 'light traps' and retain relatively high net short wave and net radiative fluxes for a 'snow-covered' surface. These high energy fluxes can provide a significant source of energy for sublimation of intercepted snow.

3. Solar angle, leaf area and canopy height govern the extinction efficiency of short wave radiation in conifer canopies. Because the extinction of short wave radiation has a strong impact on net radiation under the canopy, the canopy structure and the time of year govern the mean daily energetics at the snow cover surface and hence influence the timing and rate of snowmelt.

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